ARC Comes into Focus

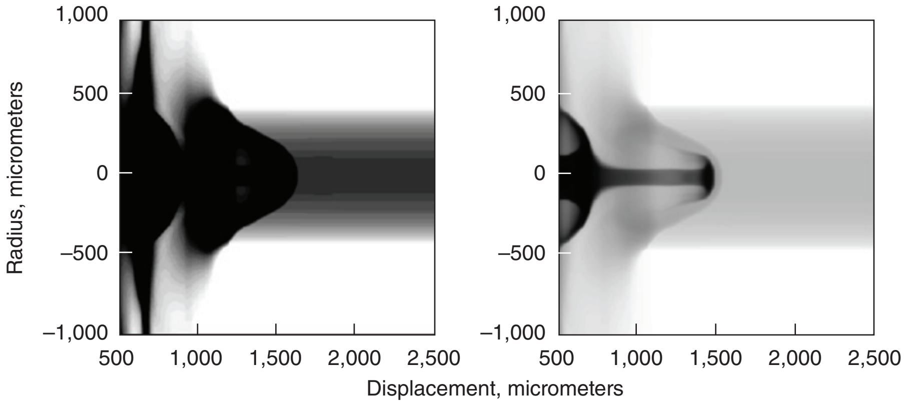
THE time it takes to complete a shot on the National Ignition Facility (NIF) at Lawrence Livermore makes the blink of an eye seem almost like an eternity. From the moment the initial laser burst is created to the completion of a typical high-energy-density science experiment, less than two-millionths of a second elapse. In the process, NIF's 192 beams deliver energy in the form of laser light that heats a target to temperatures of tens of millions of degrees and compresses it to pressures many billion times greater than Earth's atmosphere. Obtaining meaningful information about the physical processes occurring in the tiny target over timescales measured in picoseconds (trillionths of a second) has required researchers to develop a new generation of ultrafast, ultrahigh-resolution diagnostic devices. (See *S&TR*, December 2010, pp. 12–18.)

A new tool called the Advanced Radiographic Capability (ARC) will soon provide a unique capability in NIF's arsenal of detectors, spectrometers, interferometers, streak cameras, and other diagnostic instruments. ARC is a petawatt-class laser—that is, its peak power exceeds a quadrillion (10^{15}) watts—and is designed to produce brighter, more penetrating, higher energy x rays than is possible with conventional radiographic techniques. Says Greg Tietbohl, ARC project manager, "ARC allows us to see through the dense core of fuel in a target as it is being compressed."

With ARC, scientists can record a series of snapshots revealing the dynamics of materials under extreme conditions of temperature and pressure. When combined, these images will reveal changes in complex two-dimensional features over time.

Single-frame radiography using x-ray backlighters is already deployed at NIF, but this capability lacks the image quality, penetration levels, speed, flexibility, and multiframe functionality of the ARC design. ARC splits each of four NIF beams into two apertures, producing up to eight petawatt-class laser pulses that can be used to create high-energy x-ray images of the target. Each of these split beams can be adjusted independently with energy ranging from 0.4 to 1.7 kilojoules, pulse duration between 1 and 50 picoseconds, and delay up to 80 nanoseconds. "In a single beam, ARC will deliver up to 500 trillion watts (terawatts) of power—the same level of power NIF generates with 192 beams,"

Livermore's novel "folded" compressor vessel design dramatically reduces the footprint of the Advanced Radiographic Capability (ARC). Shown here is ARC project manager Greg Tietbohl next to one of the system's two compact vessels, which together hold eight compressors.



ARC allows scientists to peer inside extremely dense objects during National Ignition Facility (NIF) experiments. Simulated images illustrate how current radiographic capabilities (left) may be improved using ARC-generated x rays (right). (Courtesy of Keith Matzen, Sandia National Laboratories.)

says Constantin Haefner, the lead scientist for the ARC team. This power and flexibility put ARC in a league of its own.

Hitching a Ride on NIF

Work on the ARC concept began in 2002 as a Laboratory Directed Research and Development (LDRD) project led by Livermore scientists Chris Barty, Mike Key, and John Caird. The project's goals were to create innovative technologies that could produce petawatt pulses from modified, individual NIF beamlines and adapt them for radiographic and high-energy-density applications. Of particular interest was the possibility of using petawatt-class pulses on NIF to create the ultrashort, high-energy x rays required for x-ray radiography of laser fusion ignition and implosion experiments.

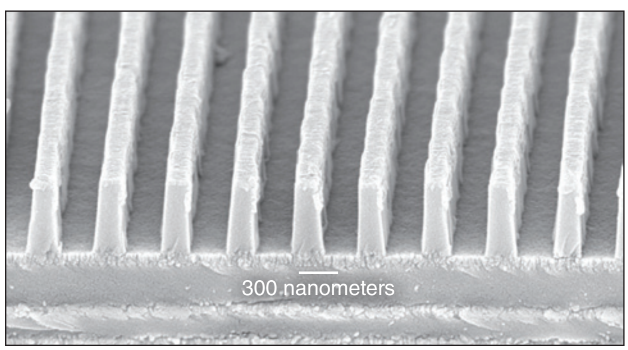
In 1996, Livermore researchers demonstrated petawatt laser pulses for the first time. Those experiments, which used a modified beam of the Nova laser system, revealed that the high-intensity laser interactions were significantly more efficient in generating high-energy x rays. (See *S&TR*, September 1995, pp. 24–33; December 1996, pp. 4–11.) Predictions based on the Nova petawatt experiments and later experiments at other facilities suggested that one-half of only one NIF beam (a split beam) could produce the necessary high-energy x rays. Achieving the same results with the existing NIF setup would require focusing more than 60 of the regular long-pulse beams onto one x-ray generation target.

ARC reaches the extreme laser intensities through chirped-pulse amplification, a common architecture for short-pulse lasers. In this process, an ultrashort laser pulse, only picoseconds or femtoseconds (10^{-12} to 10^{-15} seconds) long, is first stretched in time to reduce its intensity. The pulse's frequency content is distributed in time to create a nanosecond-long (10^{-9} second), frequency-swept (chirped) pulse that can be safely amplified without generating intensities above the damage limit of laser glass and optics. After amplification, the chirped pulse is passed through an arrangement of diffraction gratings (pulse compressor) to undo the frequency sweep and re-create the initial short pulse, thus producing a high-energy, high-power laser pulse.

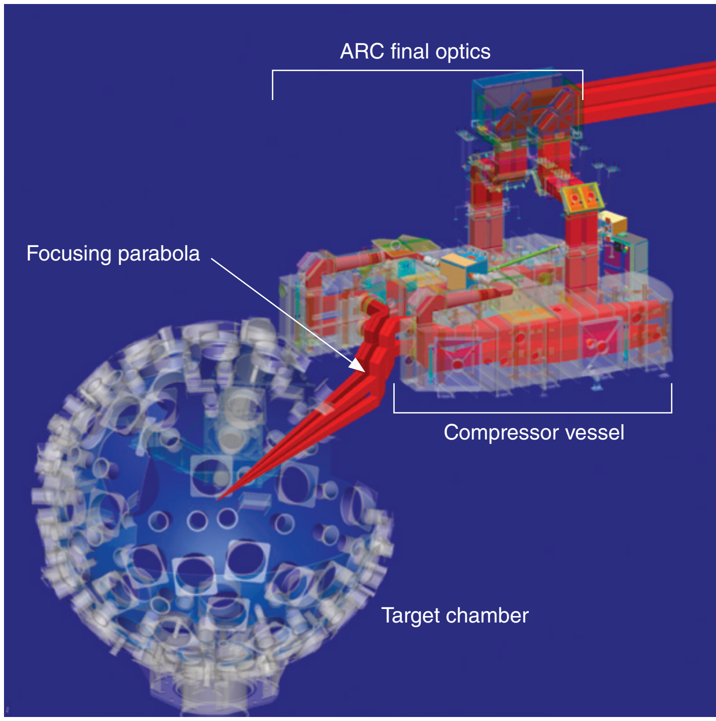
Implementing chirped-pulse amplification on NIF presented numerous challenges and required several new technologies and techniques. For example, pulse compression gratings had to be fabricated of sufficient size, efficiency, and damage resistance to handle the record-setting beam energy produced by NIF. Pulse compressors were redesigned to be 10 times more compact to be compatible with the existing NIF building and layout, and the seed laser systems were modified to be robust yet compact enough to fit into the existing NIF architecture. Techniques were also developed to capture the full characteristics of the ARC laser pulse in one shot and to allow rapid switching of designated NIF beams from long- to short-pulse operation and back.

Miles of Grooves

Prior to 2002, Livermore was already producing the world's largest diffraction gratings: 96-centimeter-wide gold gratings that were used to produce the 500-joule, petawatt pulses on Nova. However, these gratings were not large enough to handle the increased beamline energy produced by NIF. To resolve this issue, optics engineer Jerry Britten and his colleagues worked on an



This scanning electron micrograph shows the surface detail of a dielectric grating. By precisely controlling the width and height of surface grooves, Livermore researchers can produce diffraction gratings with efficiencies close to the theoretical limit and the highest possible damage threshold.



With the folded compressor design and a new laser beam centering and pointing system, ARC is compact enough to fit inside the existing architecture of NIF's 30-meter-diameter target chamber.

LDRD-funded project to develop a new multilayer dielectric grating technology and the related tools for manufacturing the required 1-meter-wide compression gratings. The new gratings allow the laser energy density to be increased by 10 times at significantly higher efficiency.

Britten notes that designing the ion-beam etcher, which he likens to a sandblasting tool for ions, was a crucial step in producing gratings that meet ARC's requirements. In particular, careful control of the width and height of surface grooves in the dielectric film is the key to obtaining efficient diffraction with the highest possible damage threshold. An astonishing 450 miles (730 kilometers) of lines cover the surface of one grating. Developing measurement techniques to confirm surface and groove uniformity together with cleaning techniques to maintain an extremely low level of surface contamination was also essential for obtaining optimum grating performance. (See *S&TR*, September 1995, pp. 24–33.) Tests at ARC's precision damage test facility have confirmed that ARC dielectric gratings are the highest damage threshold gratings of their type yet fabricated.

Space Constraints Spur Ingenuity

Grating development was not the only difficulty to overcome. Because the ARC design came together after NIF was designed and largely built, the project team faced the fundamental challenge of fitting the system in and around the giant NIF laser. Accommodating the compressors in the limited floor space near the target chamber was particularly difficult. Even with dielectric gratings placed at a high incident angle, the laser pulse compressor would be the size of a railroad car, which is more than 17 meters long. The ARC design required compressor vessels to be less than 8.5 meters long.

The answer was to "fold" the compressor to make it more compact. In the resulting design, four pairs of optical gratings are arranged on two levels, in two compressor vacuum vessels. Each split beam hits four gratings as it travels. A curved telescope mirror (parabola) focuses the set of four beams, and a mirror aims them at the specific targets. "We have developed the smallest compressor in the world for this type of laser," says Haefner. The optical gratings are designed with two groove densities, allowing them to be placed close to one another and greatly reducing the overall footprint of the compressor arrangement.

The compressor design, however, left no space for standard alignment techniques. As a result, the ARC team developed a new laser beam centering and pointing system to ensure that each ARC beam is pointed and focused precisely. Designed by Livermore optical engineer Mike Rushford to meet space constraints in the ARC vessels, the compact and reliable system won a 2009 R&D 100 Award. (See *S&TR*, October/November 2009, pp. 18–19.) As Haefner notes, "We have a nonstandard compressor and no room for standard alignment techniques, so we had to come up with nonstandard techniques." The system uses one lens and camera, rather than the standard two, for image pointing and centering information. The single camera registers where the beam came from (for centering) and where it is going (for pointing) at precisions within 10-thousandths of a degree.

Integrating Performance

Modeling, assembling, testing, and diagnosing ARC subsystems and integrating performance results have been crucial to ARC development and systems qualification. Though a diagnostic itself, ARC is complex enough to require its own diagnostic tools.

Short-pulse, high-intensity laser light is extremely difficult to measure because it is very short in time and its characteristics change when it travels through material such as lenses and glass windows. Furthermore, measuring the pulse duration would require an electrical sensor 10,000 times faster than those currently available. Instead, ARC scientists are using the laser to measure itself. The technique they use, frequency-resolved optical gating, redirects a "slice" of the laser pulse from the ARC beam through a nonlinear crystal and into a spectrometer. The sample slice provides information about ARC's pulse shape and characteristics.

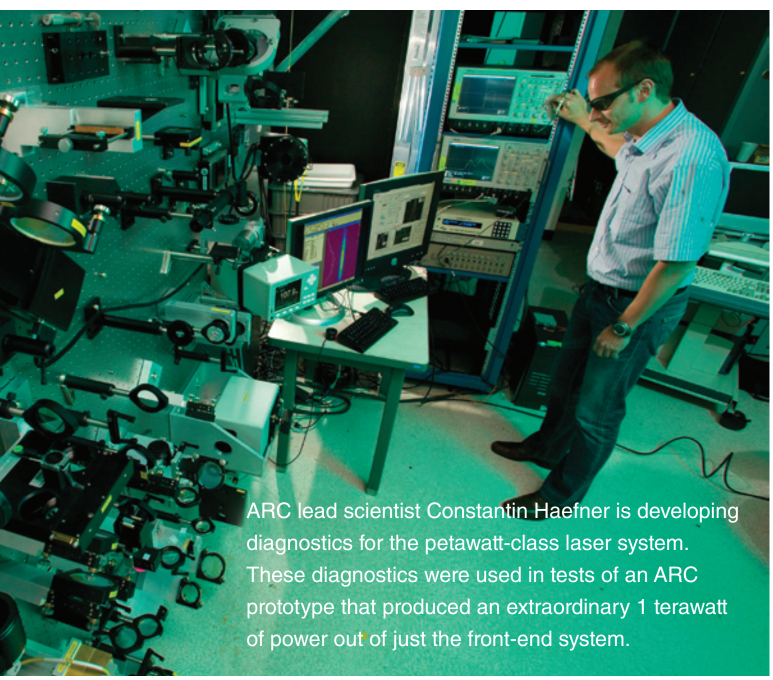
ARC's test facilities provide data to input into and compare against models for predicting the system's overall performance.

In 2009, the Livermore researchers assembled a scaled-down compressor at the output of a preamplifier module in an off-line facility to measure the performance of the full ARC injection laser system (fiber front end plus preamplifier module) as well as several key diagnostics. John Crane, the ARC systems engineer, says, “It is important to assemble the subsystems and measure how they perform together.” Results from these experiments led the team to replace the large fiber amplifiers with spectrally agile, dual regenerative amplifiers. The new injection system produces 50 times the energy of the original ARC design.

Testing also confirmed that the ARC front end can produce more than 1 terawatt of peak power. In addition, the researchers verified that a technique they developed accurately measures the amount of pulse stretch and compression. In contrast to nonlinear techniques, the new approach allows them to precisely predict and optimize ARC’s power performance without firing a single pulse. “Proving this technology works was a major achievement,” says Haefner. “Optimizing the short-pulse performance typically takes tens to hundreds of iterations.”

Illuminating a Range of Experiments

ARC’s key application, of course, will be to image, using backlighting, the time evolution of targets illuminated by NIF beams at the center of the target chamber. For backlighting, up to eight wires, each 30 micrometers in diameter, can be placed around a target to convert ARC’s ultraviolet light into a burst of x rays. The wire acts as an x-ray point source, illuminating the target, while gated imaging cameras capture an image. Each camera has a scintillator plate that lights up when x rays hit, generating visible light that can be recorded by a regular camera. The wires are arranged at different points in space and can be hit by the ARC beams delayed in time to enable high-energy x-ray radiographic capability with both multiple time frames and multiple views. Compared with the picosecond pulses produced by ARC, the camera is quite slow, so it records all the data points at once.



ARC lead scientist Constantin Haefner is developing diagnostics for the petawatt-class laser system. These diagnostics were used in tests of an ARC prototype that produced an extraordinary 1 terawatt of power out of just the front-end system.

Beyond backlighting, ARC applications are surprisingly varied and numerous. Livermore physicist Hye-Sook Park studies materials under high pressure (see *S&TR*, January/February 2007, pp. 4–11) and is one of many experimentalists eager for ARC to come online. Working with the short-pulse capability provided by OMEGA EP at the University of Rochester’s Laboratory for Laser Energetics, Park has produced high-quality radiographic data for high-energy-density experiments on tantalum. Unfortunately, she has reached the limit of conditions OMEGA can produce. This stockpile stewardship research requires pressures up to several hundred billion pascals, and for that, says Park, “We need both NIF and ARC. NIF is the only laser that can achieve such high pressures, and ARC is essential for probing materials under those conditions.”

ARC is also ideal for experiments on a state of matter found only in gamma-ray bursts, black holes, active galaxies, and the universe shortly after the big bang. Physicist Hui Chen works with a team of Livermore researchers who are using lasers to generate and study positrons. These experiments require the unique capabilities of high-power, short-pulse lasers to produce a tightly focused “photon bullet,” as Chen describes it, about 0.01 millimeters across and 0.3 to 3 millimeters long packed with trillions of trillions (10^{24}) of photons. By concentrating the energy in space and time, a short-pulse laser produces positrons more rapidly and in greater density than ever before in the laboratory. Chen’s team is already preparing for ARC experiments that will leverage its high intensity for positron and electron–positron pair plasma research not possible elsewhere.

ARC’s flexibility, precision, power, and unmatched ability to image dense materials will make it a valuable tool for exploring and advancing many of NIF’s mission areas. When complete, ARC will be the highest energy short-pulse laser system in the world. Coupled with NIF, the highest energy long-pulse laser system, the duo will facilitate experiments and capture experimental details as never before. “The Laboratory previously achieved laser records for highest average and peak laser power, and now NIF has the record for highest energy,” says John Heebner, an optical scientist on the ARC team. “Through these efforts, we are pushing the frontiers of what can be done with light.”

—Rose Hansen

Key Words: Advanced Radiographic Capability (ARC), frequency-resolved optical gating, laser beam centering and pointing system, multilayer dielectric grating, petawatt laser, x-ray radiography.

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